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WEATHERING, EROSION AND SEDIMENT COMPOSITION IN A HIGH-GRADIENT RIVER, CALABRIA, ITALY

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ABSTRACT

Source rock lithology and immediate modifying processes, such as chemical weathering and mechanical erosion, are primary controls on fluvial sediment supply. Sand composition and Chemical Index of Alteration (CIA) of parent rocks, soil and fluvial sand of the Savuto River watershed, Calabria (Italy), were used to evaluate the modifications of source rocks through different sections of the basin, characterized by different geomorphic processes, in a sub-humid Mediterranean climate. The headwaters, with gentle topography, produce a coarse-grained sediment load derived from deeply weathered gneiss, having sand of quartzofeldspathic composition, compositionally very different from *in situ* degraded bedrock. Maximum estimated CIA values suggest that source rock has been affected significantly by weathering, and it testifies to a climatic threshold on the destruction of the bedrock.

The mid-course has steeper slopes and a deeply incised valley; bedrock consists of mica-schist and phyllite with a very thin regolith, which provides large cobble to very coarse sand sediments to the main channel. Slope instability, with an areal incidence of over 40 per cent, largely supplies detritus to the main channel. Sand-sized detritus of soil and fluvial sand is lithic. Estimated CIA value testifies to a significant weathering of the bedrock too, even if in this part of the drainage basin steeper slopes allow erosion to exceed chemical weathering.

The lower course has a braided pattern and sediment load is coarse to medium–fine grained. The river cuts across Palaeozoic crystalline rocks and Miocene siliciclastic deposits. Sand-sized detritus, contributed from these rocks and homogenized by transport processes, has been found in the quartzolithic distal samples.

Field and laboratory evidence indicates that landscape development was the result of extensive weathering during the last postglacial temperature maximum in the headwaters, and of mass-failure and fluvial erosional processes in the mid- and low course.

KEY WORDS: river; sediment; erosion; weathering; Calabria; Italy

INTRODUCTION

Physical and chemical modifications of sediment, prior to final deposition, reflect all aspects of the drainage area, including source lithology, relief, climate and transport. The contribution of various source-rock types to terrigenous sediments is largely dependent on intensity of weathering, which may be different for different source rocks and relief (Basu, 1985; Johnsson, 1993), and different bedrocks react differently to chemical weathering, resulting in various landscapes and weathering profiles (Ollier, 1971; Carson and Kirkby, 1972; Dixon and Young, 1981; Dejou *et al.*, 1982; Pye, 1986; Twidale, 1990).

Drainage basins are the basic units of landscape division in fluvial geomorphology and sedimentology, defining the entire land surface area that contributes water and sediment supply to the main stream channel. Sedimentogenesis has rarely been investigated in great detail to quantify processes occurring within drainage basins, including weathering, slope-failure processes and downstream textural and compositional modifications of the detritus (Johnsson, 1993, and bibliography therein). This complex set of factors is largely involved in understanding the processes acting on mountain systems (Critelli *et al.,* 1997).

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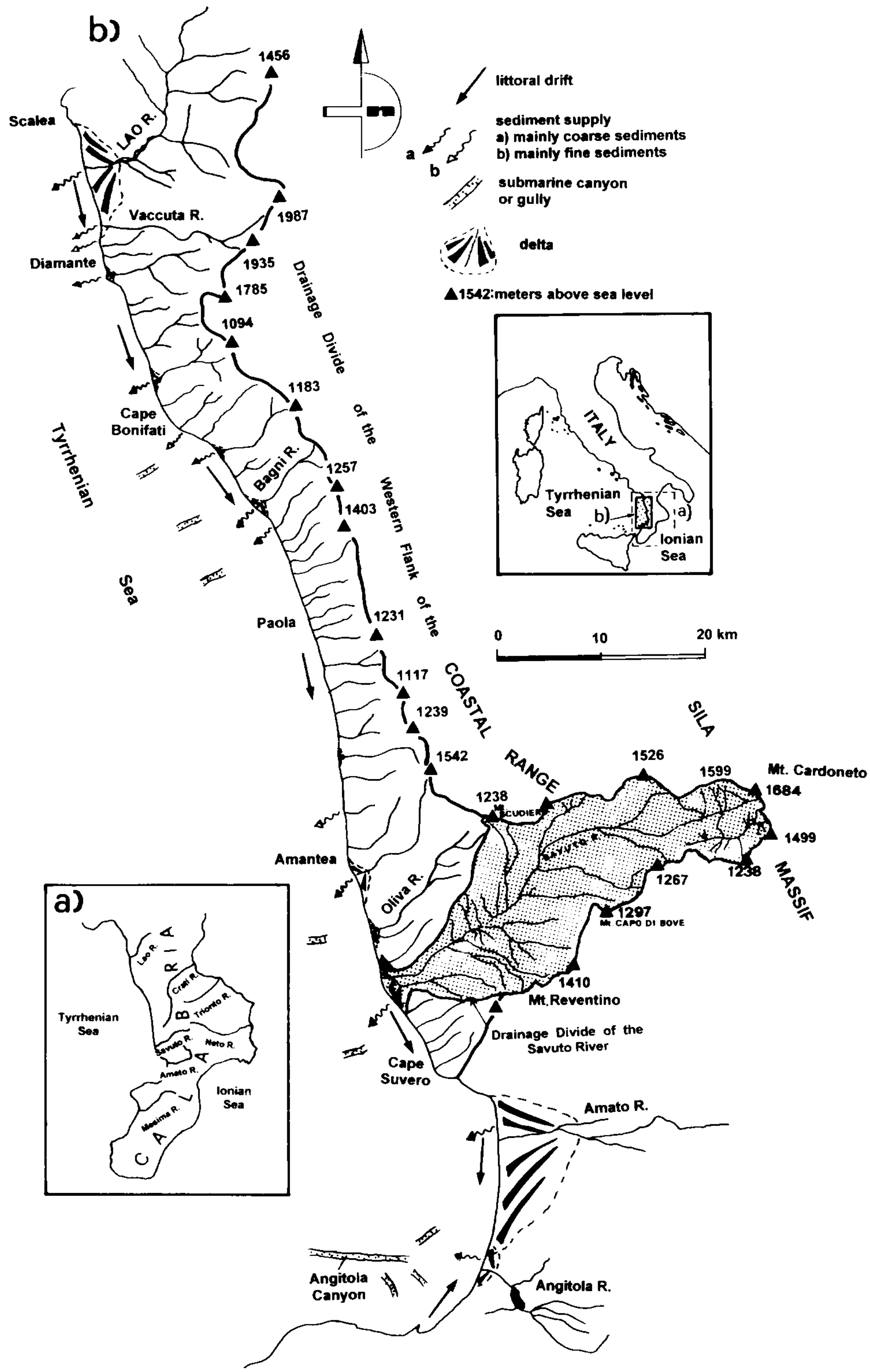

Figure 1. Location map of the western side of Calabria, showing general locations of the Savuto River drainage basin (shaded area), the drainage divide and fluvial network of the Coastal Range. Morphological information about shoreline and shelf-break after CNR (1985), Chiocci (1994) and Trincardi *et al.* (1995), and sediment supply after Le Pera and Critelli (1997)

Calabria (Figure 1) is one of the places best-suited to study relationships between landscape evolution and provenance of detritus, and to calculate mass-balance in modern high-energy environments (Ibbeken and Schleyer, 1991). In this work we report the modifications of source rocks through different sections of the Savuto River basin, western Calabria, which is characterized by different geomorphic dominant processes, and we assess the relative contribution of the different lithologies within the basin. The study area provides a good opportunity to study some of the processes (i.e. chemical weathering, slope instability and erosion) controlling landscape development of a drainage basin.

STUDY AREA

Geology and climate

The Savuto River headwaters extend on the western flank of the Sila Massif. The mid- and terminal branches of the river cut dominantly across the Coastal Range (Figure 1) which is made by a sequence of nearly flat-lying nappes (Amodio Morelli *et al.*, 1976), including Palaeozoic metamorphic and plutonic rocks, and Mesozoic to Palaeogene ophiolitic, metasedimentary and sedimentary rocks. These rocks are unconformably covered by Miocene to Quaternary deposits (Figure 2).

The bedrocks of the Savuto River drainage basin consist of two allochthonous nappe complexes. The two complexes are: (1) the Palaeozoic gneiss, with local plutonic intrusions; and (2) the Palaeozoic schist-phyllite, Mesozoic ophiolite-bearing schist, phyllite and carbonate, bearing para-autochthonous Miocene to Quaternary sedimentary terranes (Figure 2). The main thrust fault crops out in the upper portion of the drainage basin, where gneiss tectonically overlies the schist and the phyllite. Neogene normal and transcurrent faults abruptly increased tectonic uplift (0·6 to 1·2 mm a^{-1} in the last million years; Sorriso-Valvo, 1993; Westaway, 1993), and changed the orientations of drainage channels (Sorriso-Valvo and Sylvester, 1993). The bedrock of the Savuto River basin is composed of 60 per cent phyllite, 21 per cent gneiss, 10 per cent schist, 7 per cent clastics and 2 per cent plutonics and carbonate.

Calabria currently experiences a Mediterranean climate with a strong, altitude-dependent zonation of temperature and precipitation. Average annual precipitation at the Savuto River drainage basin is high, with precipitation ranging from 600–1000 mm at the lower elevations to more than 1800 mm at the higher elevations (Table I; Figure 2). The mean annual temperature ranges from 12°C to more than 16°C. The Coastal Range traps precipitation from frontal storms moving inland from the Tyrrhenian Sea, and climate ranges from Mediterranean semi-arid and moderately seasonal thermic on the piedmont to Mediterranean humid or sub-humid and moderately seasonal mesic in the mountains below 1000–1200 m. Above this altitude, both the Sila Massif and Coastal Range are humid and mesic, and snowfall alternates with heavy downpours during the winter season.

Palaeoclimatic information for the western Mediterranean, based on δ^{18}O records (Thunnel *et al.*, 1990) of the Pliocene/Pleistocene boundary, is marked by a climatic cooling. A shift to heavier glacial maxima occurs between 400 and 500 ka BP. The last sea-level lowstand, at 22 to 15–12 ka BP, was as much as 120 m lower than at present (Chiocci, 1994; Trincardi *et al.*, 1995). Thereafter the sea level started rising at a high rate during the first 4000 years of the Holocene epoch (Climatic Optimum), and is still rising and recovering the previous highstand of the Tyrrhenian period, 40–140 ka BP in the Mediterranean area. The last sea-level fall caused unloading of the toe of the Coastal Range mountain front, and large mass-failure processes on the mountain front (Sorriso-Valvo and Sylvester, 1993).

Geomorphology of the Savuto River watershed

The relief in the Savuto River watershed ranges from sea level to 1684 m a.s.l. (Mount Cardoneto; Figure 1).

Several sub-basins of the Savuto watershed have a relief ratio (Carson and Kirkby, 1972) ranging from 0·74 to 0·05. Relief ratio in the headwaters ranges from 0·74 to 0·46; in the mid-course it ranges from 0·28 to 0·05.

The drainage basin can be subdivided into two portions (headwaters/mid-course and low course/river mouth) having distinctive morphological, hydrological and geological characteristics (Table I). The

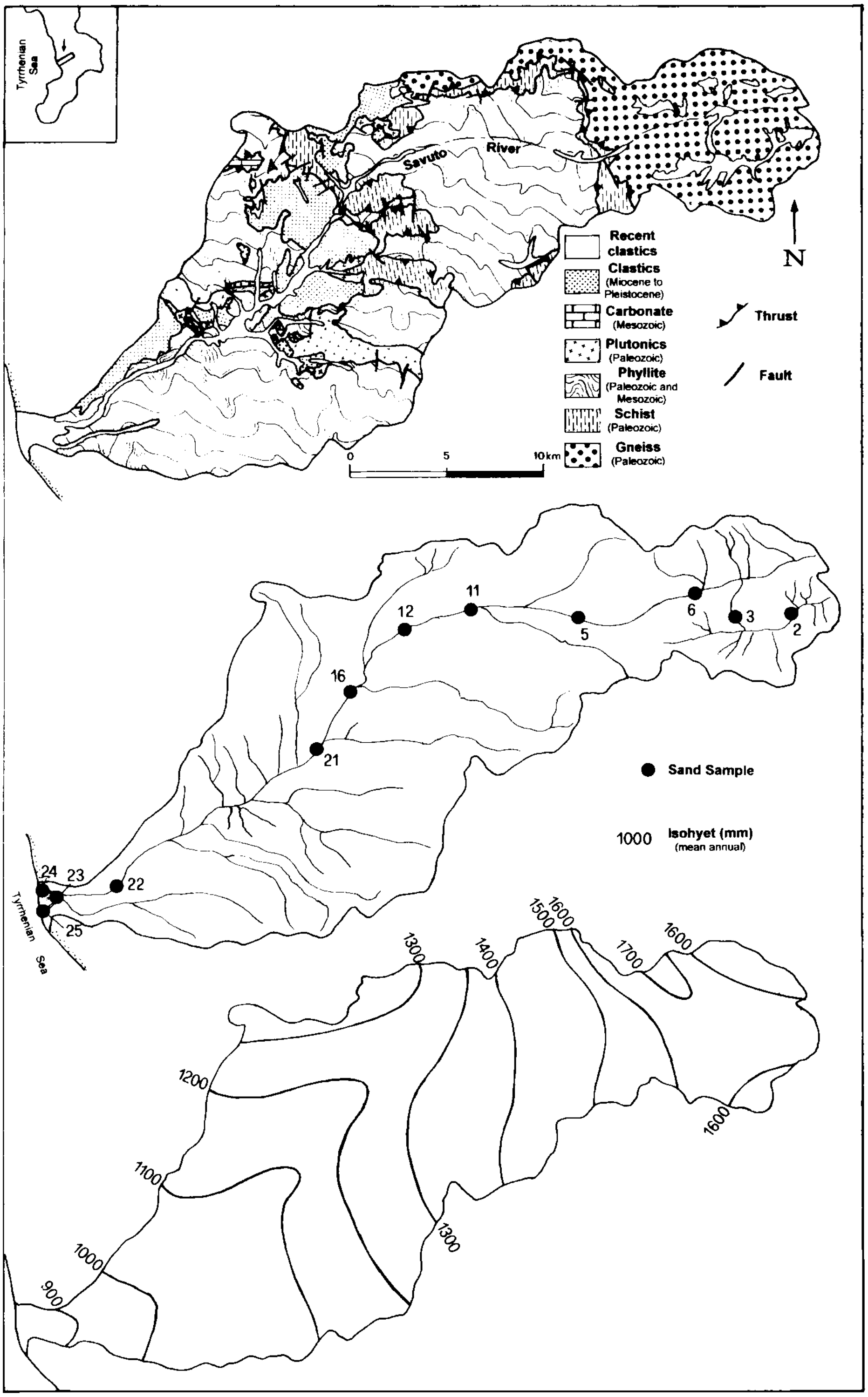

Figure 2. Geological map, location of fluvial sand samples, and isohyets of the Savuto River drainage basin

Table I. Climatic, hydrologic and physiographic characteristics of the Savuto River drainage basin

Location	Mean annual temperature* (°C)	Mean annual rainfall* (mm)	Mean annual discharge† ($m^3\ s^{-1}$)	Surface area†(km^2)	Length† (km)	Average slope† (%)
Headwaters	12–14	1400–1800				
Mid-course	14–16	1000–1400	3·72	404·7	45	2·34
Low course	>16	600–1000				

* From Versace *et al.* (1989)
† For all locations

uppermost portion of the watershed extends on the rolling highlands of the Sila Massif, and is little modified by the Quaternary tectonic uplift. The morphology of slopes is controlled by low-rate mass-wasting processes, so that a thick mantle of residual weathering product covers the basement rock. Many of the weathering mantles reported from other European sites appear to be pre-Pleistocene features (Millot, 1970). Weathering on the Sila Massif may have started in the Late Cenozoic–Quaternary (Nossin, 1973).

The tectonic control on geomorphology of the drainage basin is recognizable in the quasi-rectangular drainage pattern, in the presence of fault scarps and, principally, in the reversal of the drainage direction (Figure 3). Neotectonic features also appear clear as lineaments, the principal of which are shown in Figure 3. Most morphotectonic features indicate recent tectonic activity. The main reaches of the drainage system are gently sloping and very sinuous, with several sites where alluvial deposits are stored. The pattern of alluvial beds keeps the original arrangement, even where the direction of sediment flux has been reversed. The drainage network displays several examples of river capture. Flux reversal is due to both the headward erosion of the main branch of the present Savuto River, and to the tectonic closure of the valley bottoms (note the branch of the Lago (lake) Savuto, Figure 3).

The river passes from the headwaters to the mid-course with a sharp increment of channel slope (Figures 3 and 4), and in this transition the river flows in deep gorges. The structural control on drainage pattern is relevant (Figure 3); out of the gorges, a section with alluvium storage follows; then the alluvium deposits disappear for a long section, and reappear as the dominant feature of the valley bottom about half-way to the delta. Alluvial fans are developed at most of the confluences. Most of these fans are of the CI type (debris-flow beds; Blair and McPherson, 1994; Sorriso-Valvo *et al.*, 1998). Where phyllitic schists predominate, the ridges present a sharp crest and the slopes are affected by widespread large-scale landsliding, and its areal incidence has a maximum value of 40 per cent where this lithology occurs (Sorriso-Valvo and Sylvester, 1993). Erosion rates are consequently high, ranging from 0·6 to 0·8 mm a^{-1}, with enormous quantities of terrigenous detritus have accumulated along the Tyrrhenian shoreline (Le Pera and Critelli, 1997; Sorriso-Valvo *et al.*, 1998).

In the lower reaches, the drainage system presents a wide, braided, alluvial bed. Alluvial terraces are widespread; most of them are actually fan remnants; true terraces are up to 6 m high on the present river bottom. The river is presently in a dissection phase. The presence of Miocene calcarenite capping the schist imparts a marked asymmetry to the valley cross-profile, as it is present only on the northern side of the valley (Figures 2 and 3).

During the last million years, the base level of this river has changed in a complex way because of the alternating eustatic oscillation of sea level combined with tectonic uplift. Effects of eustatic oscillations are now difficult to assess because they simply caused covering or uncovering of low gradient zones with respect to the continent, hence during low stands the dissection affected the newly emerged lands but probably did not affect the mountain reaches. In fact, if this was the case, then multi-cyclical slope profiles should be present in the basin. During high stands, the river valleys were invaded by the sea, forming ria-type coasts, unless, as at present, debris excess transformed the stream valleys into braided streams with large fans forming the emerged parts of fan-deltas (Sorriso-Valvo and Sylvester, 1993). Tectonic uplift, on the contrary, acted as a relief-generating engine, imparting a high magnitude to all geomorphic processes (Sorriso-Valvo,

Figure 3. Geomorphological sketch of the Savuto River watershed

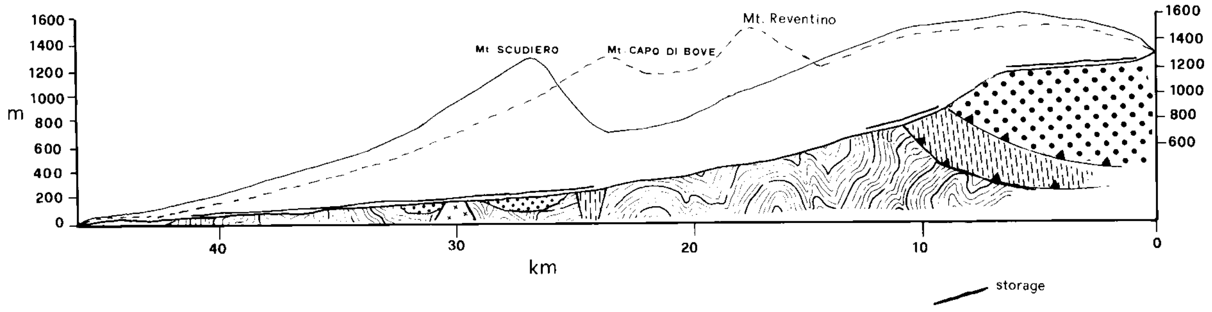

Figure 4. Equilibrium profile and geologic cross-section of the Savuto River

1989). This explains why the remnants of the landscape pre-dating the onset of tectonic uplift (Upper Pliocene–Lower Pleistocene) are preserved only in the upper and inner parts of Calabria, and are undergoing a progressive replacement by the new erosion surface. These remnants are indicated as 'palaeosurface remnants' in Figure 3. The downcutting of the main course results in headward expansion of the Tyrrhenian-side watersheds and the capture of the headwater streams of the Ionian-side watersheds. This also explains the knickpoint at the upper reaches of the equilibrium profile of the Savuto River (Figure 4): the section upstream of the knickpoint belongs to the former morphology, while the remaining downstream part is due to the present erosion cycle.

The modern equilibrium profile is rather regular, with practically no influence of possible erosion thresholds.

PETROLOGIC AND GEOCHEMICAL COMPOSITION OF SOURCE ROCKS AND DERIVATIVE SAND

Procedures and methods

We used compositional detrital modes of sand-sized sediment (expressed by suite means and standard deviations), and their geochemistry, to detect: (1) compositional variability of tributary sand, and the influence of the outcrop areas of different bedrock types on the frequency of grain types; (2) downstream compositional changes; (3) the effect of chemical weathering on upstream and mid-stream Savuto sands; and (4) the sedimentary recycling of the low-course sands.

We analysed 12 sand samples from the main channel of the Savuto River and river mouth, five bedrock samples (gneiss, schist and phyllite), and six samples from the weathered horizons (grus and soil). Fluvial sand samples come from pristine parts of active bars of the channel. River, grus and soil samples were washed then lightly sieved (using 1 ϕ intervals) to separate the sand fraction (0·0625–2 mm). The 0·25–0·50 mm size fraction was used to prepare thin sections. A total of 300 grains per sample were counted on each thin section of sand using the Gazzi-Dickinson point-count method (Ingersoll *et al.*, 1984; Zuffa, 1985). Recalculated parameters and diagrams are shown in Tables II and III and in Figures 5 and 6.

Chemical analyses were performed on fine-grained fluvial sand (0·0625–0·25 mm) and on bedrock samples. Major elements were analysed by X-ray fluorescence (Table IV). To express the extent of chemical weathering of the parent rock we used the Chemical Index of Alteration (CIA) of Nesbitt and Young (1982). This index (Table IV), calculated from both parent rock and daughter sediment chemical data, measures the molar ratio of Al_2O_3 to $Al_2O_3 + CaO + Na_2O + K_2O \times 100$. CIA values of about 45–55 indicate virtually no weathering (the upper crust has a CIA value of about 47), whereas higher values indicate intense weathering.

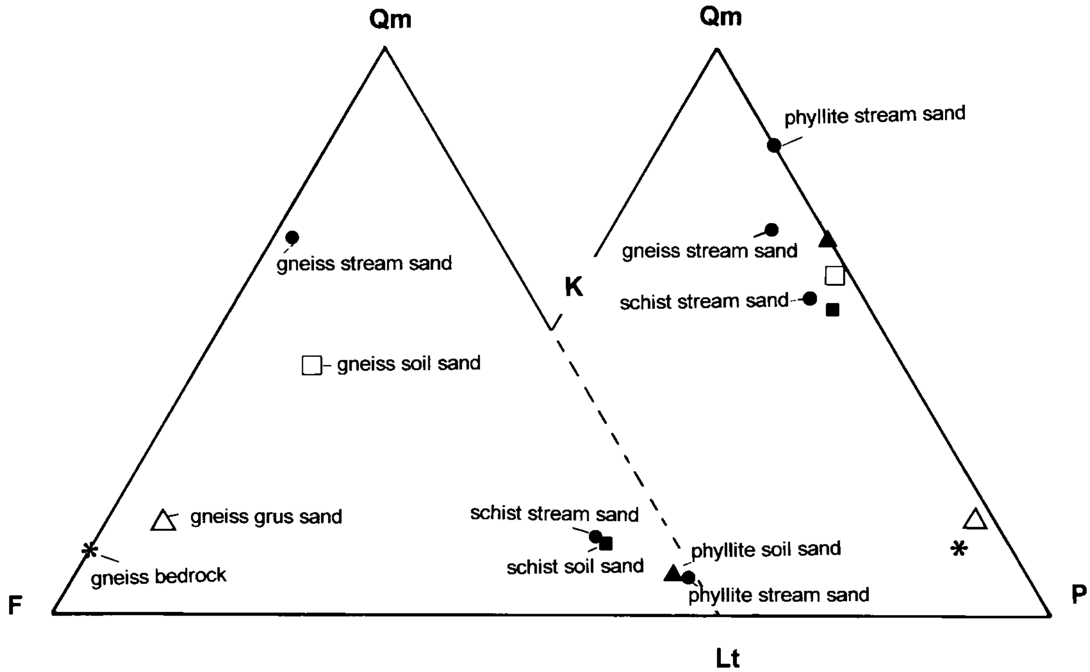

Figure 5. Triangular diagrams of the average composition of the Savuto River sand and bedrock samples. Qm = monocrystalline quartz, F = feldspars, Lt = aphanitic lithic grains, K = K-feldspar, P = plagioclase

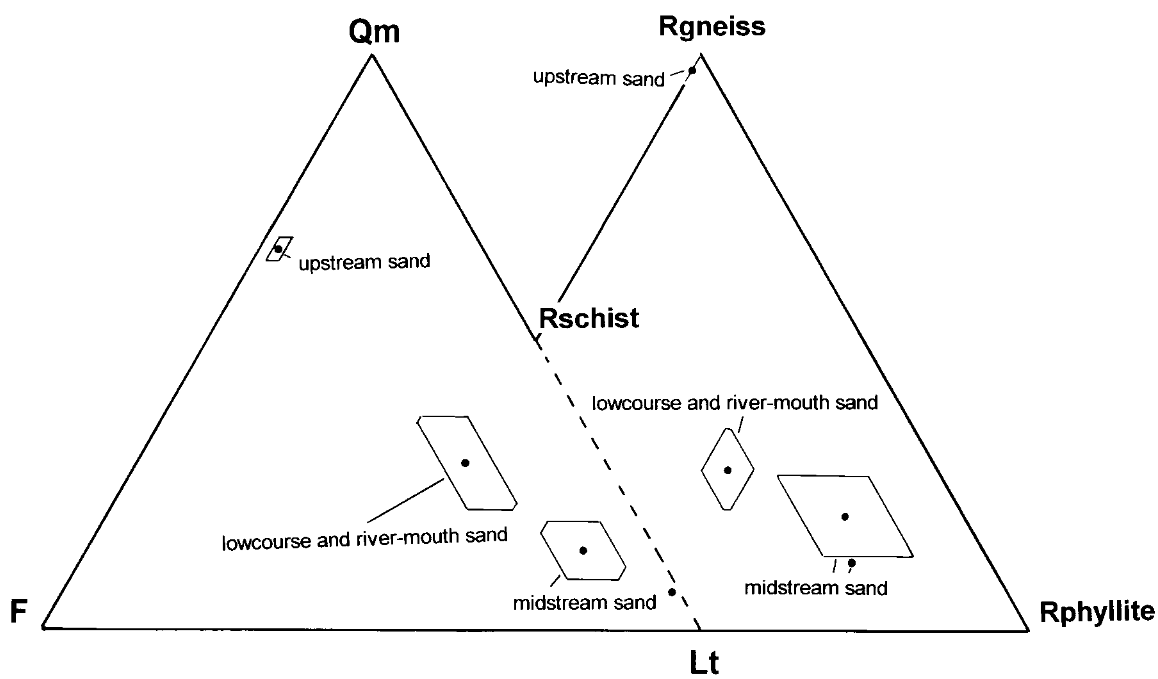

Figure 6. Triangular diagrams of the average composition of the Savuto River sand. The triangle to the right represents the rock-fragment composition (gneiss, schist, phyllite) of the lithic fraction. The dots are the mean values and polygons represent standard deviation for each fluvial sand population

Table II. Modal composition of parent rock (gneiss) and the medium sand-sized (0·25–0·50 mm) fraction of associated grus, soil and stream sand

	Gneiss						Schist				Phyllite			
	Bedrock	Grus sand	Soil sand	Stream sand			Soil sand	Stream sand			Soil sand			Stream sand
	EL49	EL50	EL51	SV3	SV2	SV6	EL43	SV11	SV12	SV16	EL44	EL46	EL48	SV5
Quartz														
Quartz (single crystal)	5·5	3·3	21	20·4	20·6	22·4	7·6	4·2	5·2	3·4	1·3	4	1·3	1·2
Quartz (fine-grained poly-crystalline)	–	0·6	1	0·4	0·2	0·2	6	0·4	6·6	0·4	2	2·3	5·3	–
In rock fragment	–	5·3	5·6	20·6	14·8	22·8	5·3	9·2	0·4	5·2	4	4·6	4·3	4·8
Total quartz	5·5	9·2	27·6	41·4	35·6	45·4	18·9	13·8	12·2	9	7·3	10·9	10·9	6
Feldspars														
Plagioclase (single crystal)	38	17	12	13·6	8·4	11·8	6·3	4·8	6·2	2·8	1	3	2·3	0·2
In rock fragment	–	21·9	9·6	4·6	2·6	3·4	3·3	3	5·4	2	1·6	1·3	1	1
K-feldspar (single crystal)	3·9	1	1·6	3·6	2·8	4·4	1	1·6	1	0·8	–	–	–	–
In rock fragment	–	0·6	–	1	1·2	1	0·3	0·8	0·4	0·4	–	–	–	–
Total feldspars	41·9	40·5	23·2	22·8	15	20·6	10·9	10·2	13	6	2·6	4·3	3·3	1·2
Lithics	–	4·3	9	0·6	1·2	1·8	66·9	64	57·8	76·2	87·9	81·2	82·9	82·2
Phyllosilicates														
Micas and chlorites (single crystal)	13	16·3	18	7·2	6	10·2	1	2·8	2·4	3·4	1·3	1·6	1·6	2
In rock fragment	–	6	3·3	8·8	3·6	6	1·3	2·6	6·2	3·6	–	2	1·3	5·6
Heavy minerals	39·6	23·7	18·9	19·2	38·6	13·4	1	5·2	6·6	1·6	0·3	–	–	0·6
Other	–	–	–	–	–	2·6	–	1·4	1·8	0·2	0·6	–	–	2·4
Total	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Table III. Recalculated modal point counts of the Savuto River sand

Sample		Qm	F	Lt	Qm	K	P	Lm	Lv	Ls	Rgneiss	Rschist	Rphyllite	P/F
Upstream sand														
SV2		68	29	3	70	8	22	100	0	0	98	2	0	0·73
SV3		64	35	1	65	7	28	100	0	0	99	1	0	0·8
SV6		67	30	3	69	8	23	100	0	0	95	5	0	0·73
	X	66	31	3	68	8	24	100	0	0	97	3	0	0·75
	SD	± 2	± 3	± 1	± 3	± 1	± 3	0	0	0	± 2	± 2	0	± 0·04
SV5		7	1	92	83	0	17	99	0	1	12	21	67	1
Mid-stream sand														
SV11		19	11	70	63	9	28	100	0	0	21	23	56	0·76
SV12		14	16	70	47	6	47	100	0	0	27	22	51	0·89
SV16		9	7	84	59	8	33	100	0	0	13	10	77	0·8
	X	14	11	75	56	8	36	100	0	0	20	18	62	0·82
	SD	± 5	± 5	± 8	± 8	± 2	± 10	0	0	0	± 7	± 7	± 14	± 0·07
Downstream and river-mouth sand														
SV21		16	15	69	51	13	36	98	0	2	16	38	46	0·73
SV22		27	26	47	50	14	36	97	3	0	31	28	41	0·73
SV23		31	22	47	58	11	31	95	3	2	31	30	39	0·75
SV24		32	24	44	57	17	26	92	2	6	30	32	38	0·61
SV25		38	20	42	65	11	24	97	0	3	35	31	34	0·69
	X	29	21	50	56	13	31	96	1	3	28	32	40	0·7
	SD	± 8	± 4	± 11	± 6	± 2	± 6	± 2	± 2	± 2	± 7	± 4	± 4	± 0·05

Qm, monocrystalline quartz; F, total feldspar = K-feldspar, K, + Plagioclase, P; L, aphanitic lithic fragments; Lm, metasedimentary lithic fragments; Ls, sedimentary lithic fragments; Lv, volcanic lithic fragments. Rgneiss, phaneritic gneiss; Rschist, phaneritic and aphanitic schist; Rphyllite, aphanitic phyllite rock fragments. P/F = plagioclase/total feldspars ratio. X = mean, SD = standard deviation

Source rocks

Bedrock. Different types of metamorphic rocks crop out in the Savuto River watershed (Colonna and Simone, 1978). We focused on gneiss, schist and phyllite, because of their larger areal distribution within this basin. Gneiss is amphibole rich or biotite–sillimanite–garnet rich (Table II). Its texture is coarse-grained and it is composed of quartz, biotite, plagioclase, iron-bearing garnet (almandine) and K-feldspar; sillimanite (fibrolite), minor zircon and opaques as accessories, and +/−amphibole (green hornblende). Both garnet and amphibole show neoformation of ferruginous weathering product as linings within and around crystals. Schist is fine- to medium-grained and consists of quartz, plagioclase, micas, minor zircon, epidote, opaques and garnet. Phyllite is very fine- to fine-grained and includes muscovite, chlorite, minor quartz, feldspar and ilmenite. The CIA of gneissic parent rock is 76·9, the value for schist ranges from 70 to 73·7, and phyllite has a value of 75·3 (Table IV).

Regolith. Regolith includes saprolite (or grus), colluvium and soil horizons. Saprolite horizons in our crystalline rocks are variable in thickness. Evidence of weathering typically extends to a depth of 50–60 m or more in gneiss, but less than 10 m in schist and phyllite. The weathering profile in biotite–garnet gneiss on the low-relief area of the Sila Massif has been detailed by Critelli *et al.* (1991) and Le Pera (1998), who showed that it can be divided into different zones: slightly weathered rock, highly weathered rock, and saprolite, overlain by kaolinite-rich soils. In the upper portions of the Savuto River drainage basin, gneiss is also zoned and frequently shows small etchplains, which are plains formed by chemical weathering and subsequent removal of regolith (Ollier, 1984).

According to Lumb (1962) and Irfan and Dearman (1978), the rock decomposition index (X_d) is expressed as $N_q - N_{q_0}/1 - N_{q_0}$ where N_q is the quartz/quartz + feldspar ratio in the weathered rock, and N_{q_0} is the quartz/quartz + feldspar ratio in the fresh bedrock. Gneissic saprolite of the Savuto watershed has a high X_d ranging from 0·5 to 0·8, similar to that studied outside the study area (Critelli *et al.*, 1991). Very thin discontinuous horizons (millimetres to centimetres thick) of ferruginous crust derive chiefly from the weathering of the most leachable Fe-Mg mineral phases (garnet, amphibole). The main mineralogical changes of weathered gneiss concern the argillification of plagioclase, Fe-oxide replacement in biotite, and new formation of kaolinite and halloysite.

Gneissic soil sand is quartzofeldspathic, with a sharp decrease of feldspar, especially plagioclase, and of heavy minerals with respect to the parent rock and grus (Table II). Sand grains in soil include quartz, plagioclase, biotite and altered almandine.

Saprolite and soil of both schist and phyllite is thinner than that developed over gneiss and, because of the steeper slopes and high incidence of slope instability, they are rapidly transferred to the stream. Sand soil from phyllite and schist is lithic and quartzolithic (Table II), respectively.

River sands

Modal composition obtained by point-counting is summarized in Tables II and III.

Sands of the headwaters. The composition of fluvial and soil sands derived from metamorphic bedrock is plotted in Figure 5; the composition of gneiss bedrock is also plotted and it is referred to the freshest biotite–garnet gneiss we have sampled. The average gneissic fluvial sand of the upstream Savuto River is quartzofeldspathic ($Qm_{66}\,F_{31}\,Lt_3$; P/F = 0·75). This sand is much richer in quartz than the genetically related bedrock, soil and grus sand. Soil and fluvial sands derived from phyllite and schist are very similar to parent rocks, and QmFLt proportions show a lithic character (Lt > Qm > F).

The transition from soil to stream sand is characterized by an increase of quartz, which is very high for gneiss, very low for schist, and nearly zero for phyllite. Feldspar and lithic proportions depend on the parent bedrock; feldspar content from gneiss and phyllite decreases from soil to stream sand, while it remains nearly constant for schist-derived sands. Lithic grains always show a decrease from soil to stream for all the parent rock during the transition from soil to stream sands.

Sands of the mid- to lower branches. Sand of the downstream and river-mouth branches is quartzolithic ($Qm_{32}F_{23}Lt_{45}$), reflecting derivation from mixed high-grade metamorphic/plutonic and sedimentary and metasedimentary source rocks (Figure 6).

Table IV. Estimates of the major element abundances of some selected parent rock and the fine-sized fraction of the associated fluvial sand. CIA is the Chemical Index of Alteration (Nesbitt and Young, 1982) calculated in molecular proportion

	Phyllite		Gneiss				Schist					
				Stream sand				Stream sand				
Element	Bedrock SV4	Stream sand SV5	Bedrock SV7	SV2	SV3	SV6	Bedrock SV9	SV11	SV12	Bedrock SV13	Bedrock SV15	Stream sand SV16
H_2O	0	5·23	2·53	4·56	4·71	3·5	3·35	4·05	3·95	3·65	1·94	4·24
Na_2O	1·2	0·63	0·64	0·54	0·67	2·7	1·22	1·3	0·72	1·71	1·43	1·5
MgO	2·47	5·01	1·94	5·8	4·05	3·52	3·1	3·25	1·68	2·29	2·97	3·02
Al_2O_3	23·96	19·05	15·39	15·9	18·8	13·67	19·87	19·51	15·76	18·58	19·66	19·37
SiO_2	57·62	51·96	68·41	50·09	56·15	65·73	57·84	57·41	65·83	63·66	59·46	58·53
P_2O_5	0·13	0·14	0·09	0·22	0·14	0·04	0·17	0·22	0·21	0·06	0·21	0·17
K_2O	5·08	2·99	3·22	1·32	1·92	1·42	3·66	3·48	5·78	3·31	3·69	3·66
CaO	0·31	1·33	0·09	1·9	1·65	2·52	1·16	1·35	0·69	0·19	1·17	1·62
TiO_2	1·17	2·42	0·88	6·3	2·67	0·8	1·42	1·28	0·79	0·85	1·34	1·02
MnO	0·05	0·19	0·07	0·22	0·13	0·06	0·09	0·09	0	0·05	0·08	0·08
Fe_2O_3	8·01	6·72	4·37	10·37	6·99	4·12	3·54	5·91	2·56	4·48	7·29	4·38
FeO	0	4·33	2·36	2·78	2·11	1·92	4·58	2·13	1·98	1·16	0·7	2·41
Total	100	100	99·99	100	99·99	100	100	99·98	99·99	99·99	100	100
Moles												
Al_2O_3	0·235	0·186	0·15	0·155	0·184	0·134	0·194	0·191	0·154	0·182	0·192	0·19
CaO	0·005	0·023	0·001	0·033	0·029	0·044	0·011	0·024	0·012	0·003	0·02	0·028
Na_2O	0·019	0·01	0·01	0·008	0·01	0·043	0·019	0·02	0·011	0·027	0·023	0·024
K_2O	0·053	0·031	0·034	0·014	0·02	0·015	0·039	0·036	0·061	0·035	0·039	0·038
CIA	75·3	74·4	76·9	73·8	75·7	56·7	73·7	70·5	64·7	73·6	70	67·8

Using a plot to emphasize percentages of gneiss, schist and phyllite rock fragments (Table III; Figure 6), the rock fragment population of the upstream sand plots to the Rgneiss apex with a mean of $Rgneiss_{97}$ $Rschist_3$ $Rphyllite_0$ with a very small variation field. Schist percentage, within gneissiclastic sand, derives from thin and fine-grained schistose lenses within gneiss or mylonitic bands. The relative frequency of rock fragments of the mid-stream sand ($Rgneiss_{18}$ $Rschist_{19}$ $Rphyllite_{63}$; Figure 6) has a larger variation field than upstream, low-course/river-mouth sands. Downstream and river-mouth sands plot in a narrow variation field ($Rgneiss_{28}$ $Rschist_{32}$ $Rphyllite_{40}$).

Sand composition is controlled by the physiographic province in which samples have been collected (Figure 6). Samples collected in the Sila Massif are quartzofeldspathic or lithic-rich, while Coastal Range sands consist of a mixture of all three components. A downstream increase in compositional maturity is shown by the increase of the quartz/lithic fragment ratio (Qm/Lt) from metamorphiclastic mid-stream sands (average Qm/Lt = 0·19), to mixed metamorphic/sedimentary derived distal sands (Qm/Lt = 0·58). River-mouth sand has 25 per cent gneiss, 30 per cent schist, 40 per cent phyllite, and the remaining 5 per cent are plutonite, fine clastics and carbonate rock fragments.

Seven upstream and mid-stream sand samples (Table IV) and five bedrock samples from gneiss, schist and phyllite were analysed to obtain chemical composition. Gneiss and schist contain large amounts of SiO_2, Al_2O_3 and MgO due to high quartz and biotite content, K_2O content almost always exceeds CaO content, while Na_2O is considerably more abundant than other major elements such as MnO, TiO_2 and CaO. FeO and Fe_2O_3 are also abundant due to mafic minerals content. Phyllite samples contain more Al_2O_3, Fe_2O_3 and K_2O than the other bedrock samples.

Chemical composition of some sand samples of the Savuto River is compared with the chemical composition of specific parent rock. TiO, FeO, Fe_2O_3, MgO and CaO show the greatest changes from bedrock to fluvial sediment. Other elements can be variably enriched or depleted with respect to the source rock: SiO_2 is equal or enriched in fluvial sand, Al_2O_3 generally decreases, while FeO and Fe_2O_3 contents vary greatly. Other major elements can be concentrated in more stable minerals, which may cause large variations in the element abundance in bedrock or sediments. The CIA value in phyllite-derived sand decreases to 74·4; in the gneissic sands it ranges from 56·7 to 75·7, and in the schist-derived sands from 64·7 to 70·5.

DISCUSSION

It has been demonstrated that, in a humid climate, chemical weathering acts vigorously on sediment composition derived from crystalline rocks, destroying labile minerals, such as feldspar and Fe-Mg phases, and lithic fragments (Basu, 1976; Grantham and Velbel, 1988; Nesbitt and Young, 1989). Quartz is much more resistant to chemical weathering and it increases in relative abundance in the more humid climates because of the release of quartz grains from the weathering of the rock fragments (Young *et al.*, 1975). Basu (1976) has shown that lithic fragments in the sand framework are the best climatic and/or palaeoclimatic indicators since they are the most sensitive to destruction by chemical weathering processes. Nesbitt and Young (1996), and Nesbitt *et al.* (1996) show that feldspar depletion becomes progressively more pronounced as chemical weathering proceeds, and the resulting sands become progressively less representative of the source rock mineralogy, and shifted towards a quartzose composition.

Ibbeken and Schleyer (1991) found that, in southern Calabria where climate is invariant with respect to the Sila Massif, the effects of chemical weathering are diluted by overwhelming consequences of slope instability, with huge landslides that constitute the most important sources of immature debris for fluvial transport and deposition.

In the Savuto River drainage basin, both chemical weathering and mass-wasting occur on source rock, representing the main processes affecting composition of the main-channel sand and sediment delivery to the coastal environment. CIA indicates that chemical weathering is particularly high for the gneiss of the headwaters. According to Carson and Kirkby (1972) and Grantham and Velbel (1988), as areas with steep slopes have higher erosional rates, there the residence time of soil in the weathering profile is shorter. This seems to apply to the Savuto River basin where slopes with low angle of declivity (the headwaters) have the maximum extent of chemical weathering, whereas steep slopes have a lower extent of weathered horizon

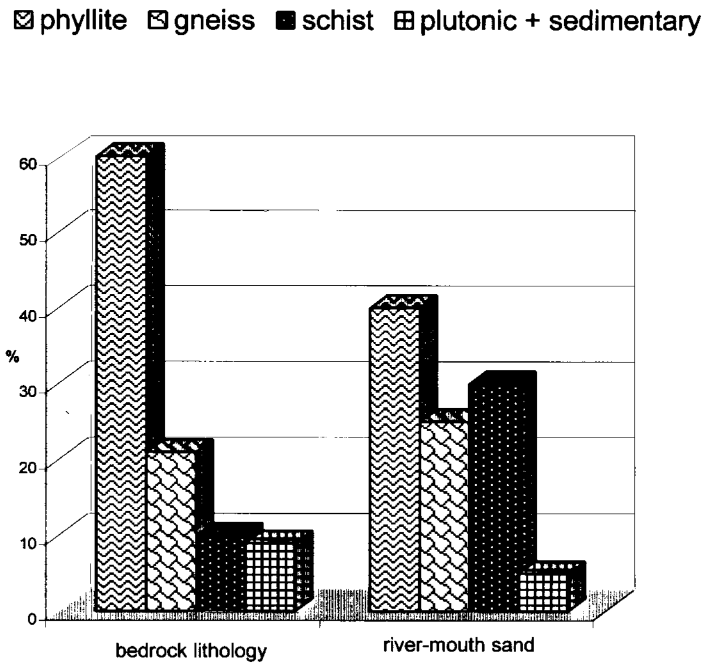

Figure 7. Bedrock composition in the drainage area of the Savuto River basin and of the river-mouth sand population

(mid- and lower reaches). Indeed, the Savuto headwater branches erode exclusively the most intensely weathered zone of the gneiss, generating a fluvial sand that is much more quartzose than related parent rock. As expected, the sands are compositionally similar to the sand-sized detritus of the soils mantling bedrock rather than to the fresh bedrock or grus, indicating a maturation process of the detritus during its storage within the soil column (Figure 5). This trend (Table II, Figure 5), resulting in substantial modifications of quartz:feldspar:lithics, and of quartz:plagioclase:K-feldspar proportions, is generated as chemical weathering proceeds (Nesbitt and Young, 1984; Nesbitt *et al.*, 1997); it has also been documented by Cullers *et al.* (1988), who found a similar relationship between the sand-sized fraction of soils and related stream sands, for gneissic parent rocks from southwestern Montana. When exposed to chemical weathering attack, soil and grus are extensively leached and stored feldspathic detritus readily alters to more quartz-rich sand even before entering into the dispersal fluvial system.

The mid-course branches of the Savuto River erode dominantly phyllite and schist, generating lithic sand (Figure 6). Sub-basins in this portion have steeper slopes and a narrow and deeply incised valley, thus surface runoff is faster than on the upstream gentler slopes. Intense mechanical erosion, due to large and frequent mass-movements of the valley flanks, rapidly transfers large amounts of phyllitic and schistose detritus, abruptly diluting the gneissic contribution to sediment supply. In the low course this mixture is homogenized with detritus coming from rocks of the low course (Figure 2). Sand is quartzolithic, enriched in quartz with respect to mid-stream sand (Figure 6). Chemical effects of weathering certainly exist, as indicated by the CIA, but schist and phyllite-derived stream sand plots very close to the related soil sand (Figure 5), testifying to a poor mineralogical zonation of the profile. This indicates that the present conditions of Savuto slopes do not represent an equilibrium phase of the weathering–erosion mutual control (Carson and Kirkby, 1972). As erosion is deeper in the mid-course, parent rock there is relatively fresher than in the upper and low course, as indicated by the lower differentiation of river sands with respect of parent rocks.

River-mouth sand summarizes the final compositional results of all processes acting within the Savuto River basin. Comparison between areal bedrock occurrence with proportions of each rock type at river-mouth sand suggests that gneissic rocks after 45 km of transport preserve their areal proportions (Figure 7). Schistose

detritus has high durability during transport, increasing by at least 20 per cent with respect to their areal occurrence. On the other hand, phyllitic detritus decreases by at least 20 per cent with respect to its areal proportions, probably because source rocks supply finer grain-sized sediments than sand-sized detritus.

CONCLUSIONS

There is a general relationship between the sediment yield of a major denudation region, and the history of the weathering, climate and topography of a mountainous region such as Calabria. The sediment yield in the Savuto River drainage basin is related to a source area with high precipitation rate, abruptly changing topography, weathered metamorphic rocks, and where residence time of soils is dependent upon topography.

This study revealed that the Savuto River drainage basin is characterized by at least two different morphological reaches, having different landscapes evolution.

(1) In gentle slope areas of the Sila Massif province, corresponding with the headwaters, erosion is transport-limited. Soils accumulate to great thickness and the residence time of soil is long. The resultant grus and soil are quartz-rich, and their erosion produces sand that is much more quartzose than the source rock. During chemical weathering the alkali elements are largely leached from the soil profile.
(2) Within the Coastal Range province, corresponding with the middle and lower course, steeper slopes lead to weathering-limited erosion. Soils are thin and bedrock is commonly exposed at the surface. Landslides are the most important contributors to the faster transport rates. Under these conditions sands are less chemically weathered and their composition resembles that of source rocks. The Coastal Range produces sands of lithic composition where phyllite and schist occur, but of quartzolithic composition in the southern part of the range where the Savuto River reworks the Tertiary and Quaternary sediments.

Combined field and laboratory evidence indicates a landscape evolution, over time, of the headwaters as the result of extensive weathering during Pliocene to Quaternary climatic oscillations, whereas landscape development of the lower reaches is weathering-limited and dominantly affected by present-day mass-failure and fluvial erosional processes.

In conclusion, the composition and geochemistry of fluvial sand, in relation to transport process and source lithology and topography, shed from a tectonically active source area in a temperate climate can be useful to gain a better understanding of landscape evolution and drainage basin response over more prolonged periods.

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